Modeling and Prediction of the Arctic Environment

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Outline

1. Rationale – Guiding Arctic Focused National Requirements
2. Arctic Modeling Capabilities:
   - Naval Research Laboratory
   - DOE Office of Biological and Environmental Research (BER)
   - CICE Consortium
3. Regional Arctic System Model (RASM)
   - Process-level simulation
   - Dynamical Downscaling for Sub-seasonal to Decadal Prediction
4. Summary

Arctic Focused USN Policies

Appendix 3: Arctic Roadmap Implementation Plan

1.1 Strategy, Policy, Missions and Plans

1.1.7: Conduct Arctic intelligence and front-end-security assessment and provide report to CNO to inform POM-16 and annually thereafter

2.2 Science and Technology

2.2.6: Increase ONR's Arctic Research Efforts and brief milestones annually to Chief of Naval Research. Improving the Navy's ability to understand and predict the Arctic physical environment at a variety of time and space scales.

2.3 Environmental Observation and Prediction

2.3.5: Encourage research into and development of comprehensive Arctic System Models

(February 2014)

U.S. NAVAL RESEARCH LABORATORY

Global Ocean Forecast System (GOFS) 3.1: two-way coupled ocean-ice

- HYbrid Coordinate Ocean Model (HYCOM): ~7 km mid-lat resolution, 41 layers
- Community Ice CodE (CICE): ~3.5 km resolution at the North Pole,
- Atmospheric forcing from NAVy Global Environmental Model (NAVGEM)
- Navy Coupled Ocean Data Assimilation (NCODA): assimilate real-time ocean and ice observations
- GOFS 3.1 runs daily at Navy DSRC, 24-hour update cycle and **7-day forecasts**

Studies performed with the Navy's Arctic Cap Nowcast/Forecast System showed significant improvement when model was initialized with CryoSat-2 ice thickness.

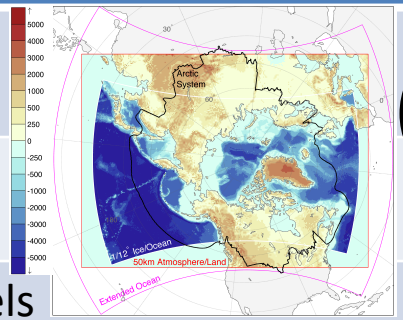
Allard et al. 2018

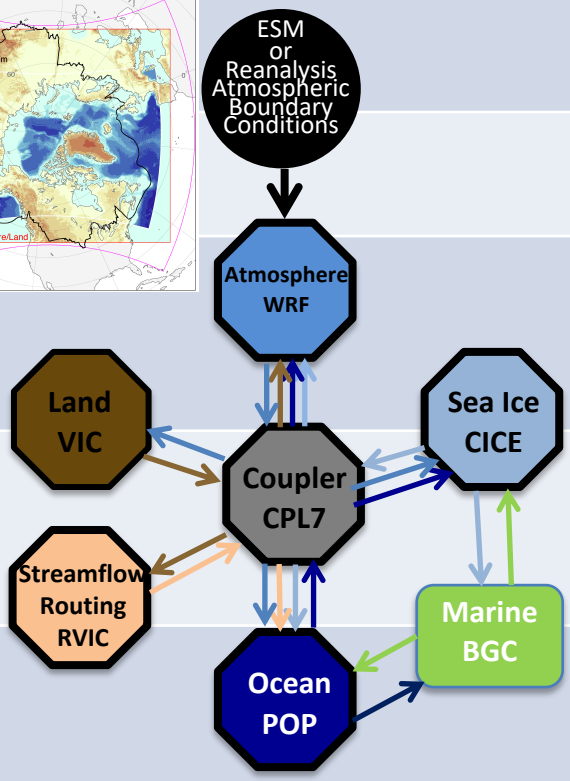
Navy Earth System Model (NESM)

- Fully coupled atmosphere (NAVGEM), ocean (HYCOM), sea ice (CICE) system with data assimilation for atmosphere and ocean/ice.
- Participating in the North American Multi-Model Ensemble Subseasonal eXperiment (SubX) to provide subseasonal forecast guidance to NCEP Climate Prediction Center forecasters
- Each week provide 4 member time-lagged **45-day NESM forecasts**
- Leverage work to also provide long term sea ice forecasts to the National Ice Center

Regional Arctic System Model (RASM) Overview

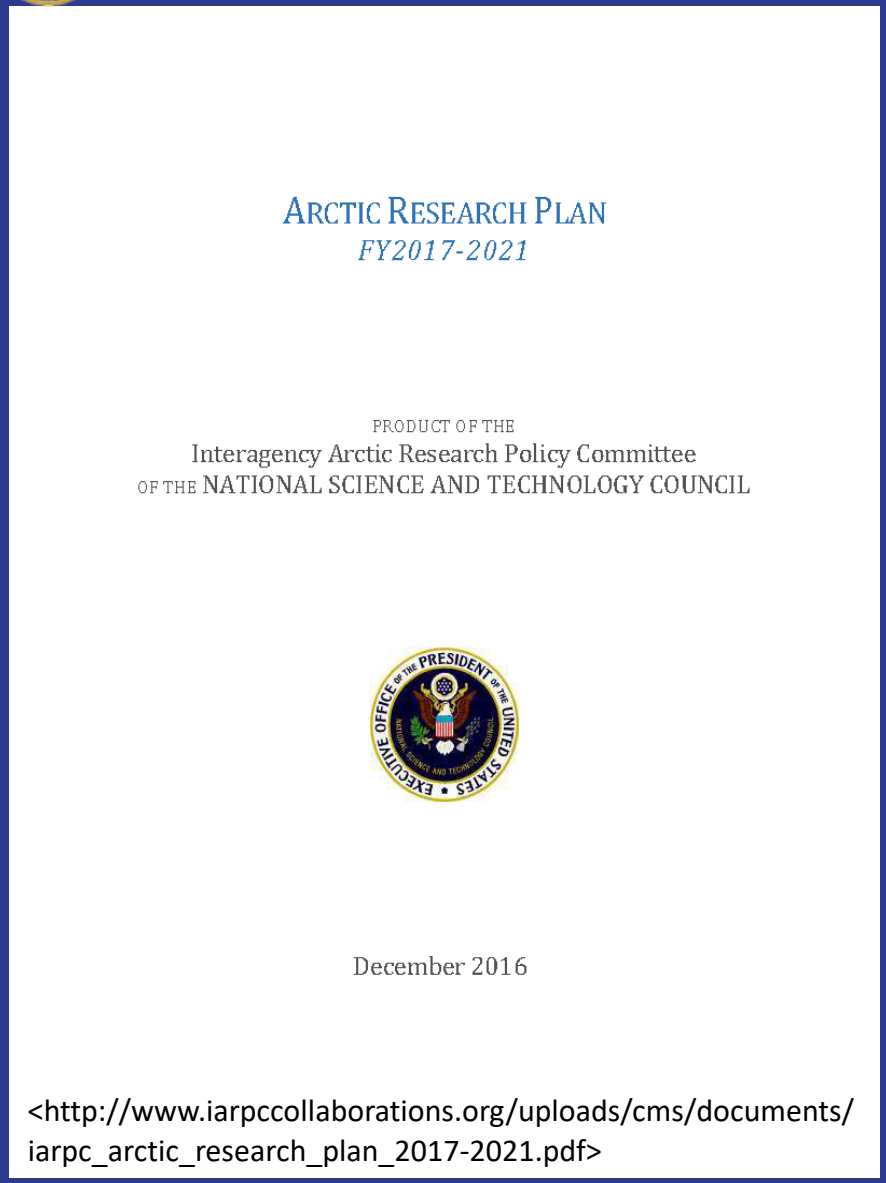
RASM 2.1 (RBR)	Code	Configuration **Pan-Arctic domain including all the sea ice covered ocean in the NH (down to ~30°N in N. Pacific and ~45°N in N. Atlantic)**
Atmosphere	WRF371	50km / 25km, 40 levels
Land	VIC	50km / 25km, 3 Soil Layers
Ocean	POP2	1/12˚ (~9km) & 45 / 60 levels 1/48˚ (~2.4km) & 45 / 60 levels (20m@5m/100m@5m)
Sea ice	CICE5+	1/12˚ or 1/48˚, 5 thickness categories Anistropic(EAP)/Isotropic(EVP) rheology
Coupler	CPL7x	Flux exchange every 20 minutes, inertial resolving with minimized lags.





RASM-G: POP + CICE + CPL7 + CORE2 (atm+runoff)
G9: 1/12°&45; GV9: 1/12°&60; G2: 1/48°&45; GV2: 1/48°&60

Arctic Focused National Policies


ARCTIC RESEARCH PLAN
FY2017-2021

PRODUCT OF THE
Interagency Arctic Research Policy Committee
OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

December 2016

<http://www.iarpccollaborations.org/uploads/cms/documents/iarpc_arctic_research_plan_2017-2021.pdf>

Arctic Research Plan FY2017-2021 has 9 goals:

2. Advance process and system understanding of the changing Arctic atmospheric composition and dynamics and the resulting changes to surface energy budgets;

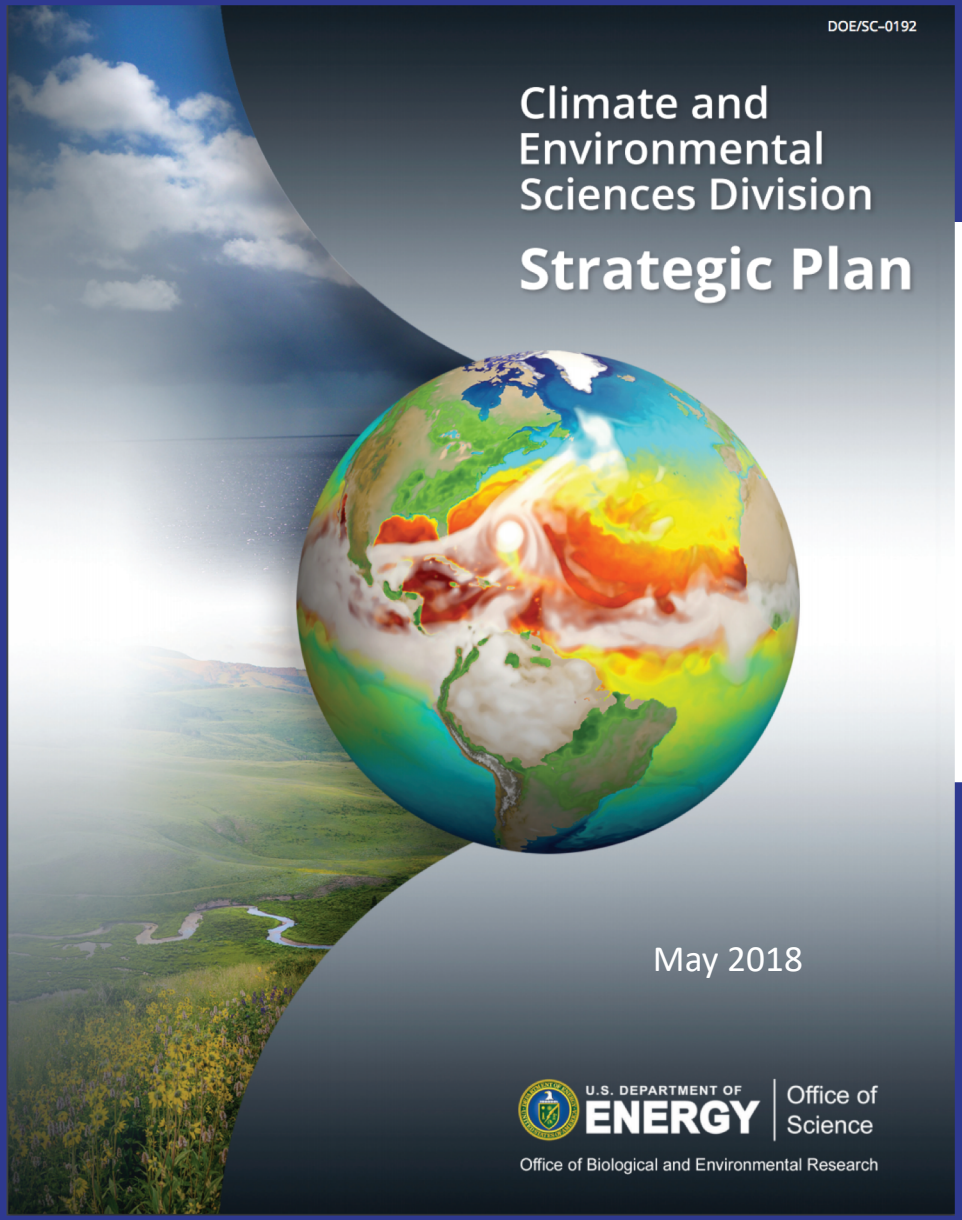
3. Enhance understanding and improve predictions of the changing Arctic sea ice cover;

4. Increase understanding of the structure and function of Arctic marine ecosystems and their role in the climate system and advance predictive capabilities;

5. Understand and project the mass balance of glaciers, ice caps, and the Greenland Ice Sheet, and their consequences for sea level rise;

9. Enhance frameworks for environmental intelligence gathering, interpretation, and application toward decision support.

Arctic Focused DOE Efforts

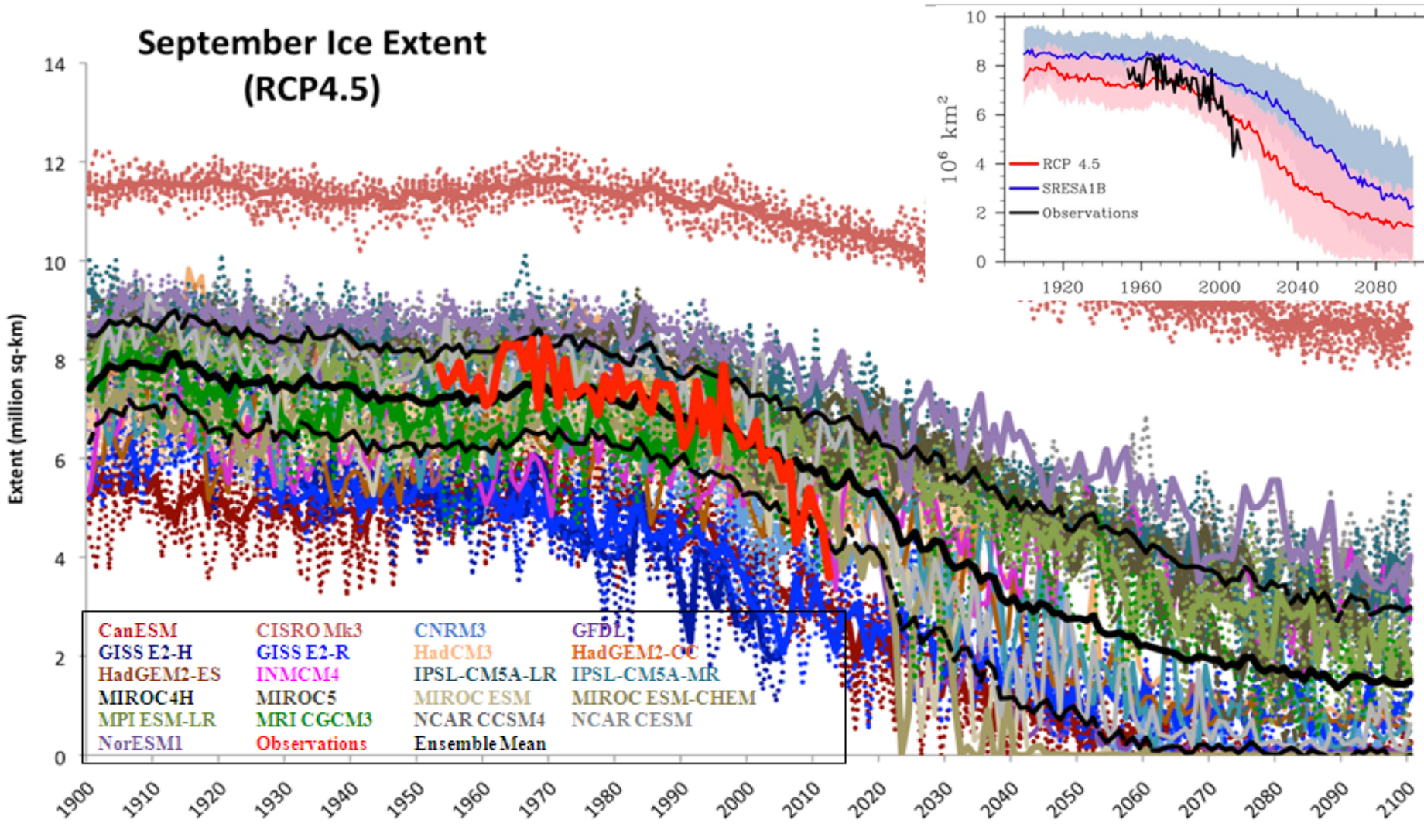


Strategic Plan 2018–2023

High Latitudes Scientific Grand Challenge. Understand and quantify the drivers, interactions, and feedbacks both among the high-latitude components and between the high latitudes and the global system to reduce uncertainties and improve predictive understanding of high-latitude systems and their global impacts.

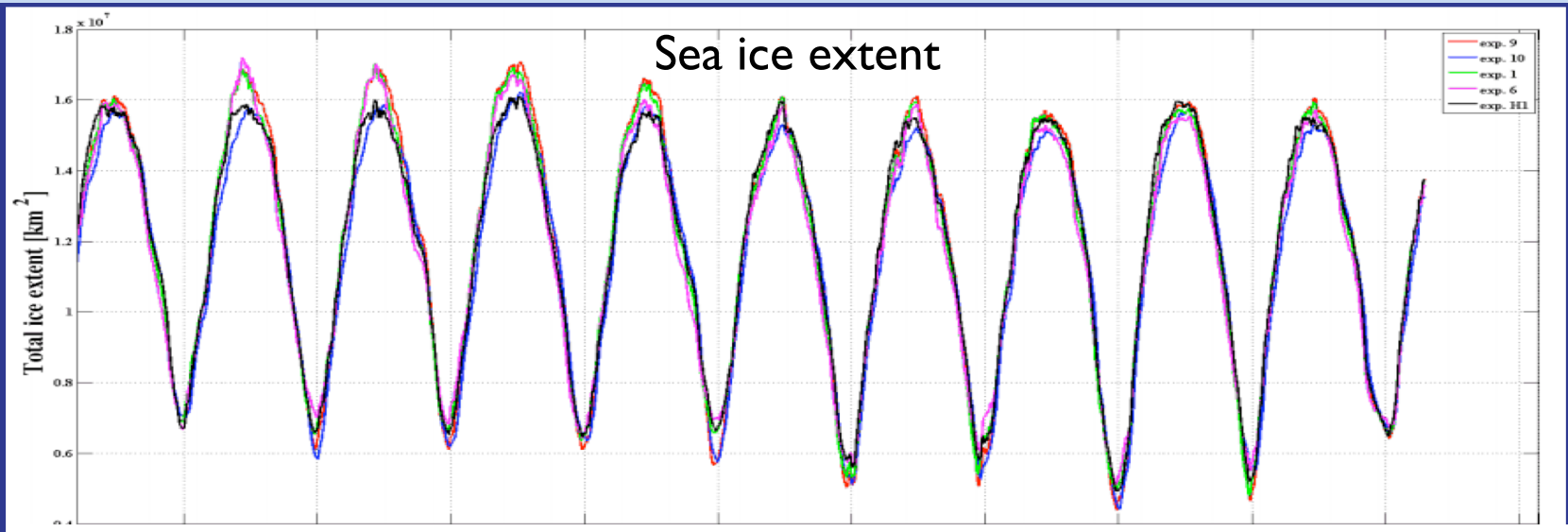
It is one of the five Grand Challenges

Global Climate / Earth System Model Predictions

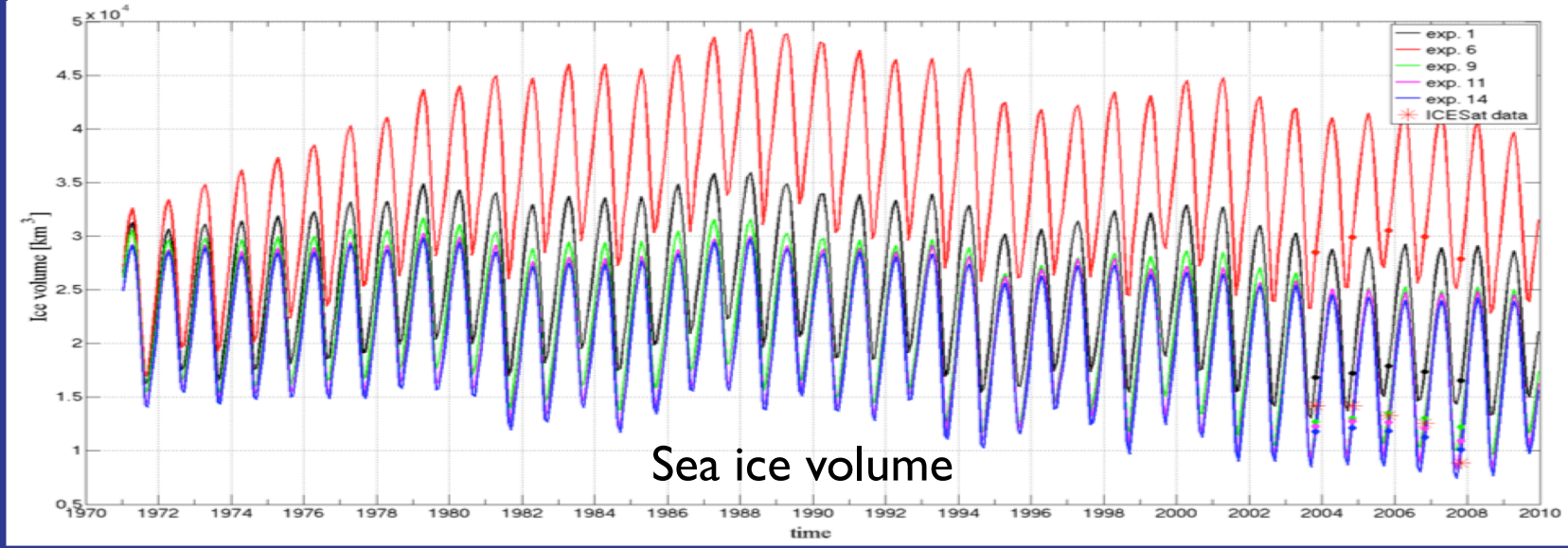


CMIP5 models are less conservative wrt sea ice but the spread has increased relative to CMIP3
(Stroeve et al., 2012)

RASM G-case Results: Parameter Space Sensitivity



Small sensitivity in simulated sea ice extent relative to thickness/volume



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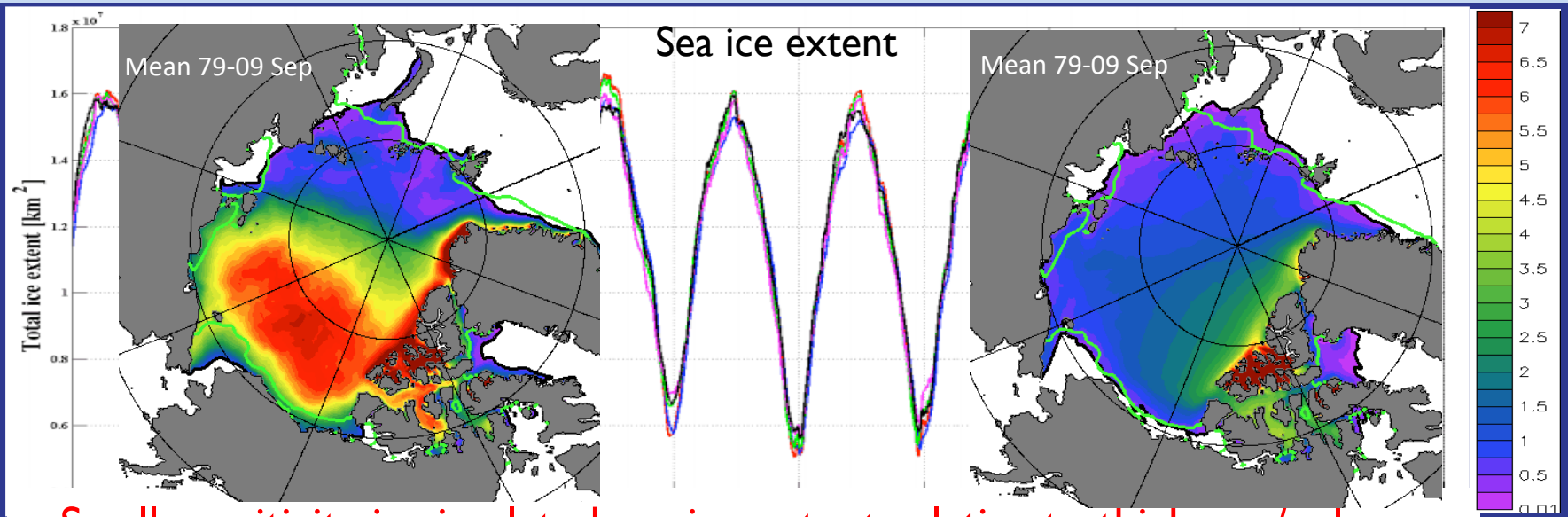

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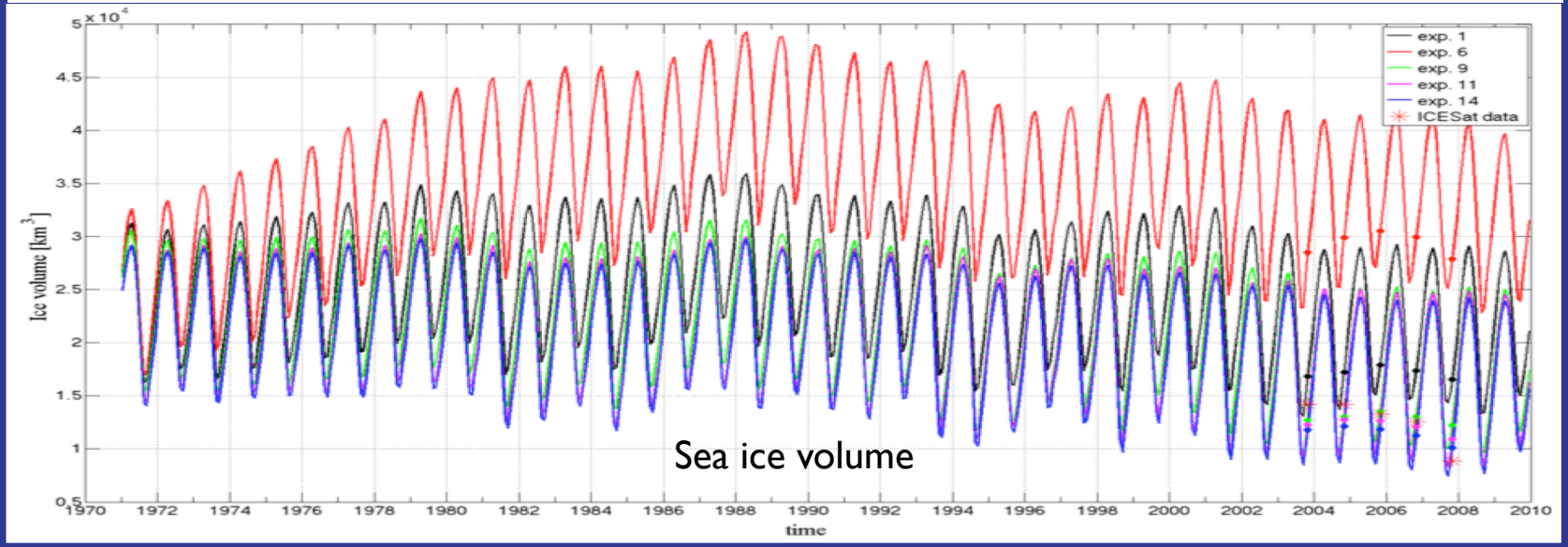
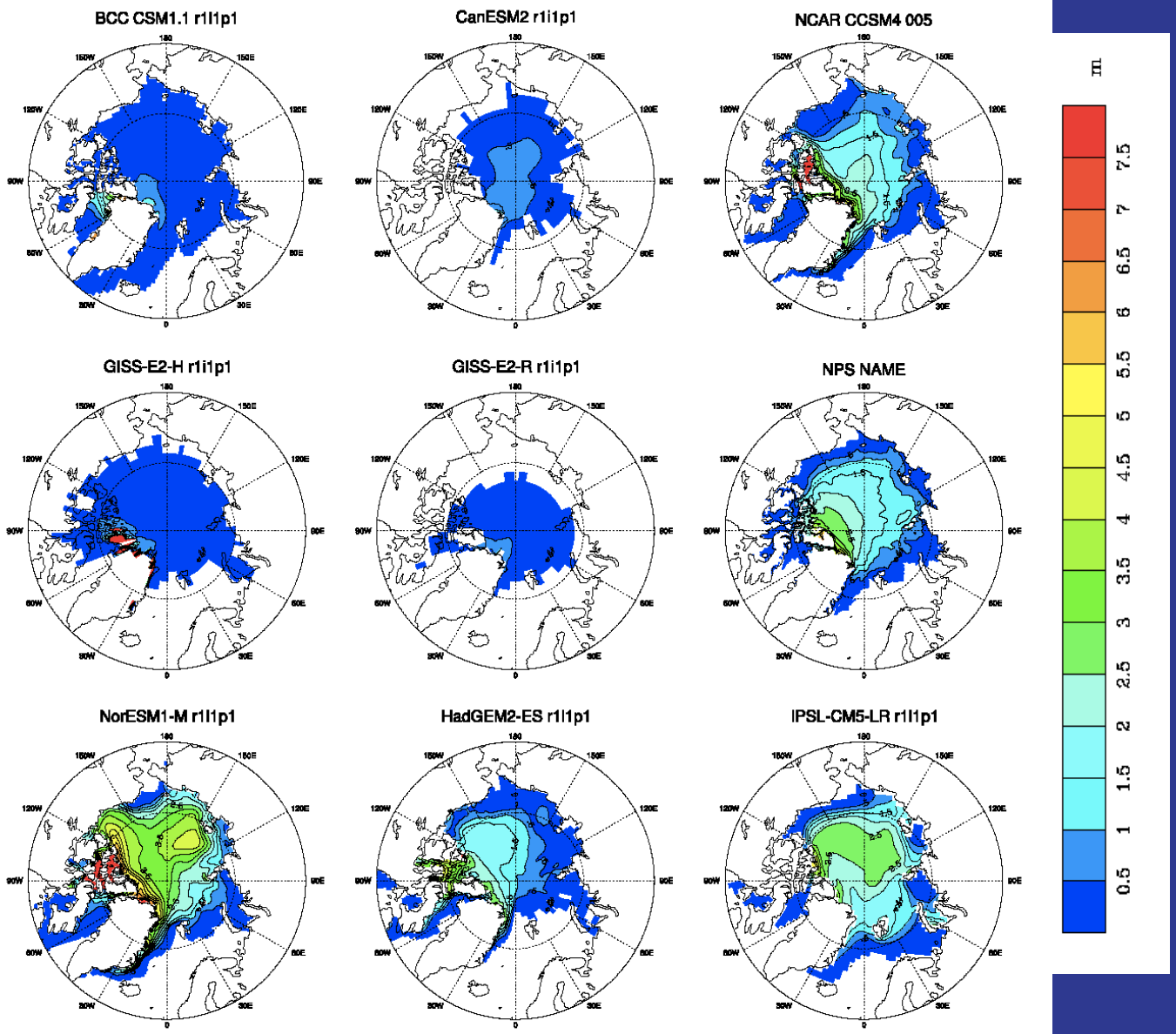


Climate Models' Arctic Predictive Capabilities



September 5-year (2000-2004) mean sea ice thickness (m) from CMIP5 and NAME models.

(Maslowski et al., 2012)

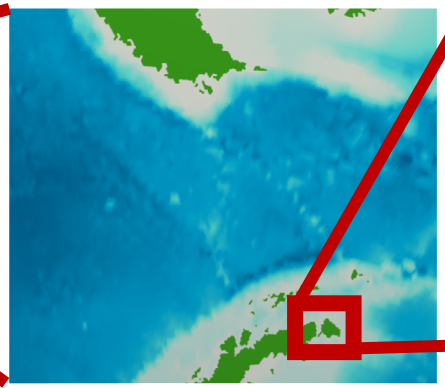
DOE Energy Exascale Earth System Model (E3SM) Variable-Resolution Meshes

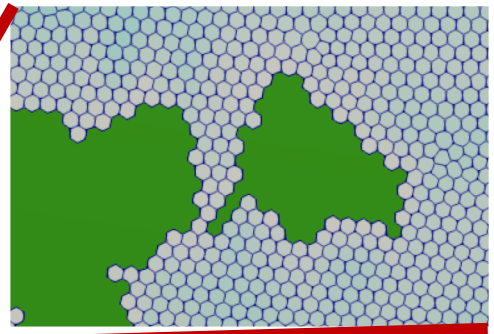
E3SM-Southern Ocean

Low-resolution
30-60 km cells

High-resolution
Southern Ocean
6 km cells

Resolution	Horizontal grid cells
Global low-resolution	0.2 million
Global low-res. plus enhanced Southern Ocean	1.1 million
Global high-resolution	3.7 million

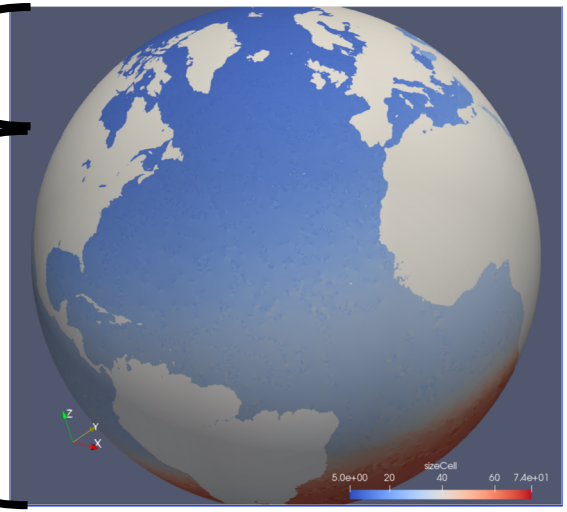


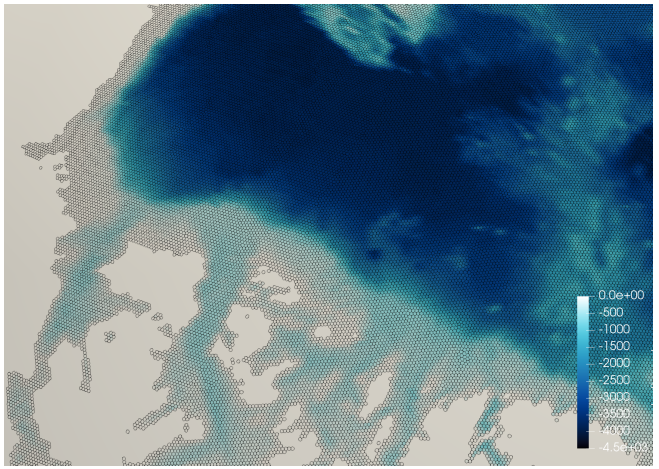


E3SM-ARRM

High-resolution
Arctic Ocean
10 km cells

Low-resolution
30-60 km cells

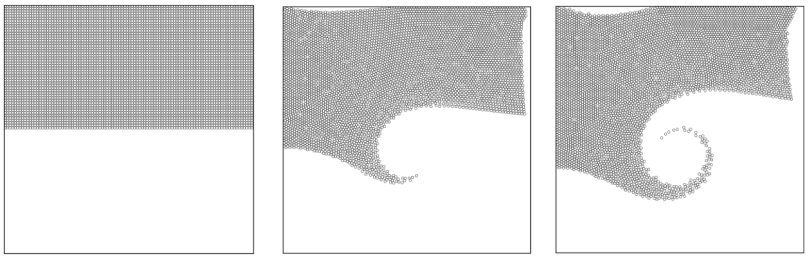




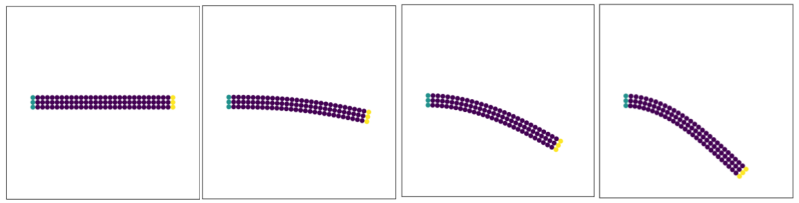
Discrete Element Model for Sea Ice (DEMSI)

- Pilot project for DOE, Office of Biological and Environmental Research
- Developing a prototype discrete element sea ice model for global climate models
  - Better utilization of new heterogeneous computing architectures
  - Improved representation of intermittent, anisotropic sea-ice dynamics
- Utilizes the LAMMPS molecular dynamics code as the dynamical core
- Many challenges ahead, including coupling, developing a contact model suitable of sea-ice, element deformation
- Team:

  LANL: Adrian Turner, Andrew Roberts, Min Wang
  SNL: Kara Peterson, Dan Bolintineanu, Dan Ibanez (SNL)
  NPS: Travis Davis



Vortex wind forcing test case



Cantilever testcase without fracture

CICE Consortium

to enhance sea ice model development for and by the community

New Community Sea Ice Model Development

… a sampling

- Fast ice
- Improved treatments of snow
- Biogeochemistry
- New rheologies
- Variational-principle ridging and morphology
- Floe size distribution
- Tide- and wave-ice interactions
- Thermodynamically consistent melt ponds
- Under-ice ponds
- Interacting icebergs
- Data assimilation
- C-grid capability

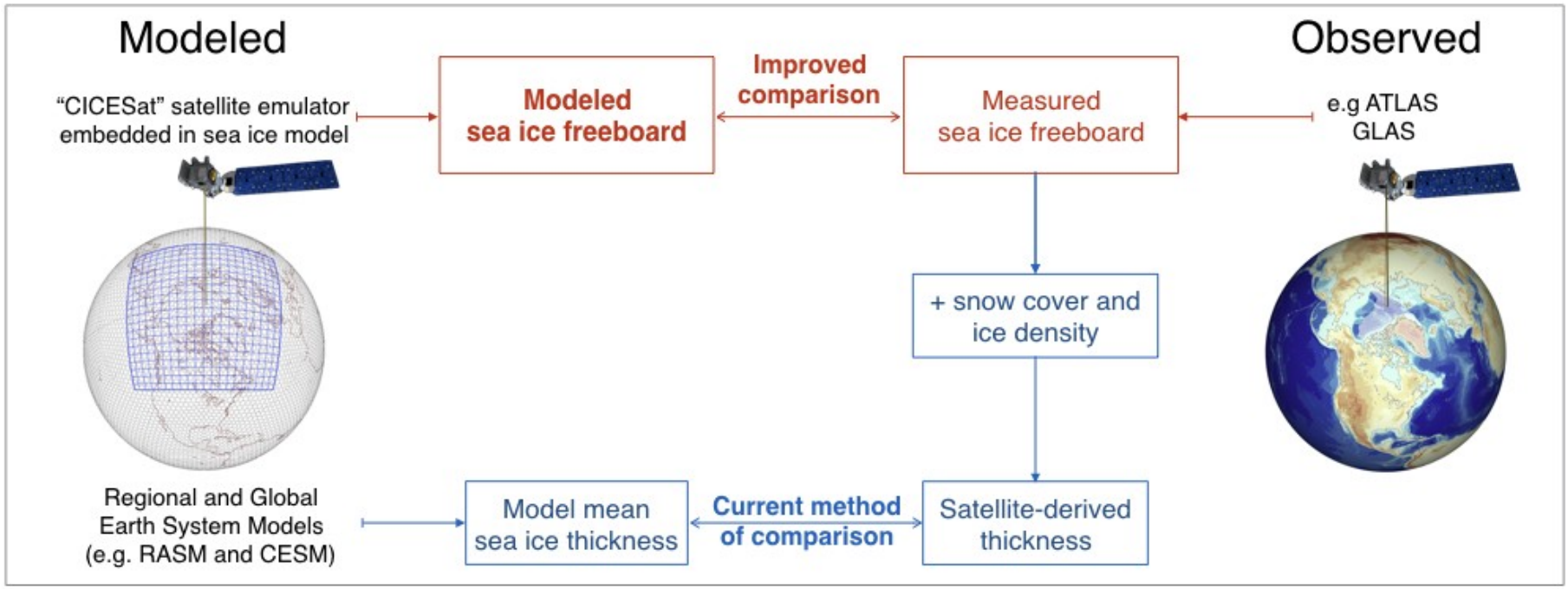
NAVAL POSTGRADUATE SCHOOL

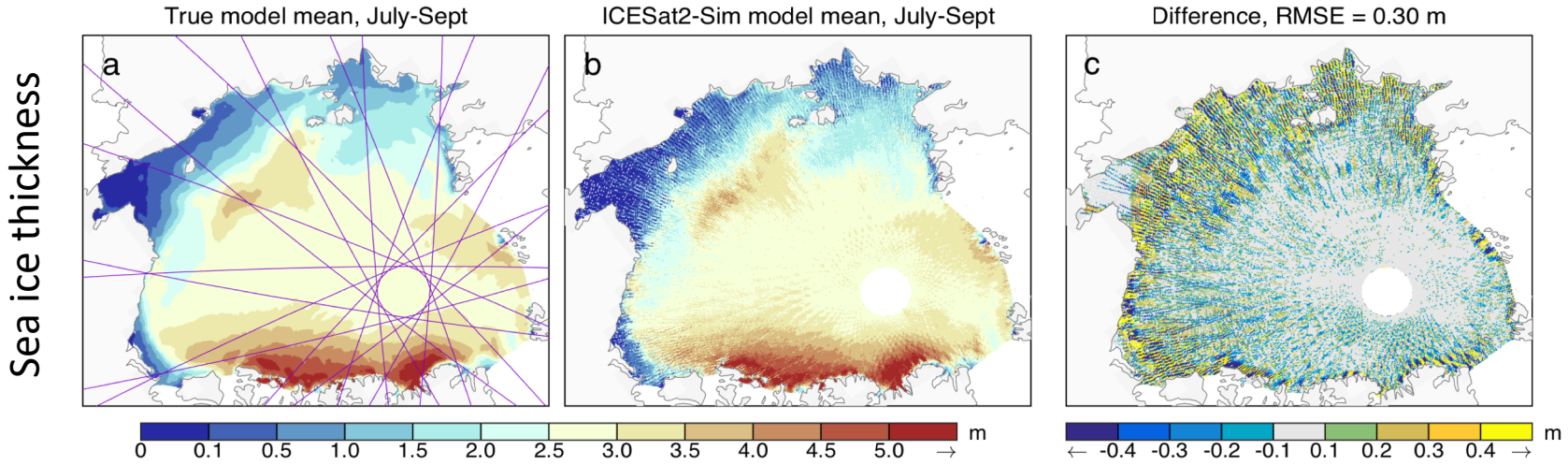
U.S. NAVAL RESEARCH LABORATORY

Environment Canada

RASM Satellite Emulator

What do we mean by a satellite emulator for sea ice models?

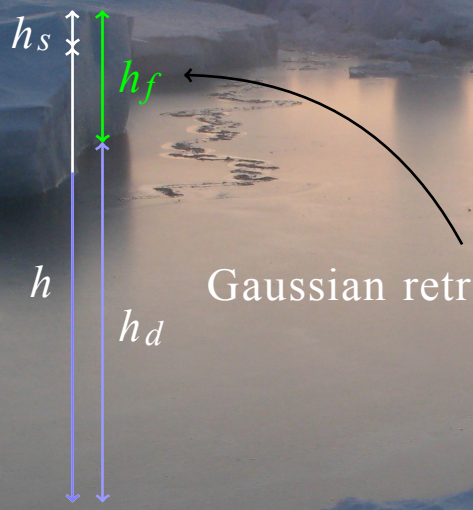




Courtesy Andrew Roberts

New Analysis Techniques for CICE: Satellite Emulators

h is not measured directly by satellite altimeters
However, freeboard is measured, and it is known in models



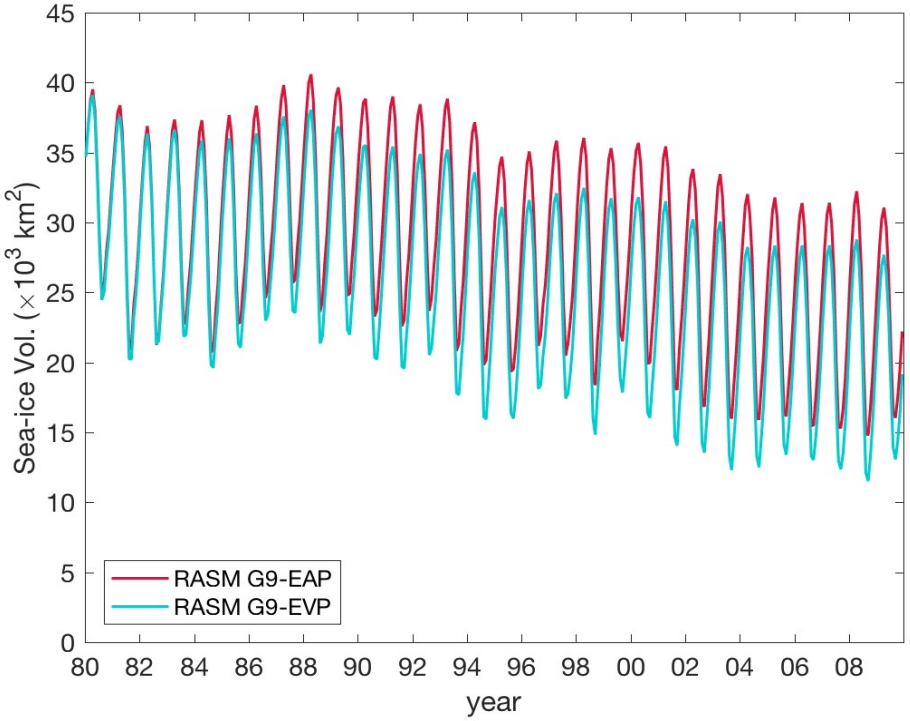
Gaussian retrieval $\breve{h}_f$ for ICESat and ICESat-2

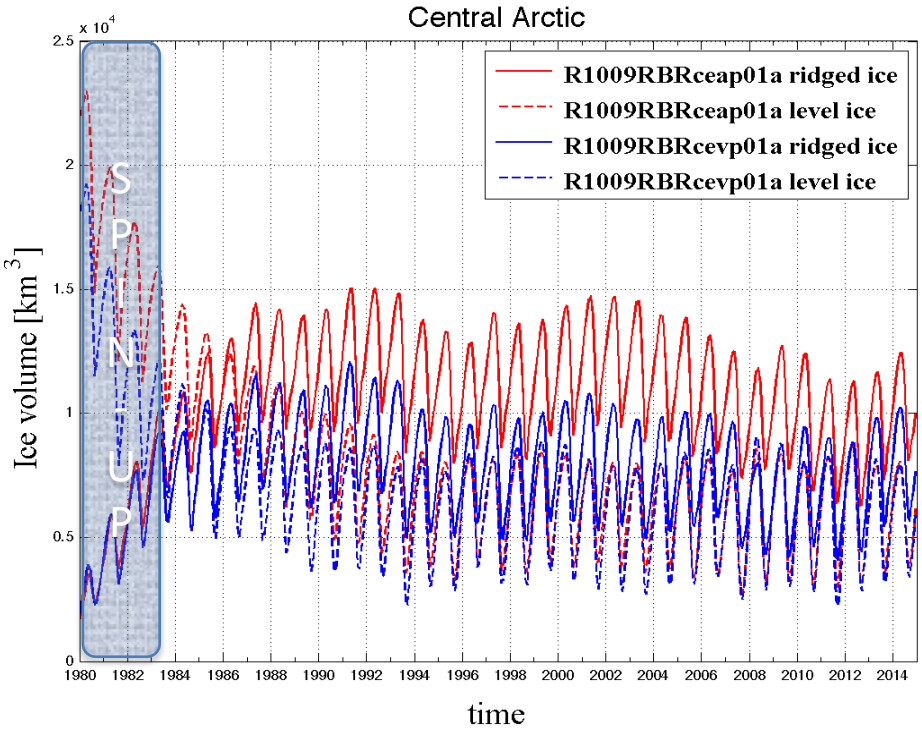
Courtesy Andrew Roberts

Freeboard $\breve{h}_f$ has a measurement error of ± 0.14 m for ICESat, but $\breve{\rho}$ and $\breve{h}_s$ are poorly known.
However, freeboard $\bar{h}_{fm}$ can be calculated in Earth System Models
Hence, instead of comparing $g(h)$ in a model with $\bar{h}$ from the satellite, we compare $\bar{h}_{fm}$ with $\breve{h}_f$

RASM G-case Results: Parameter Space Sensitivity

Forced / coupled model sensitivity to sea ice rheology

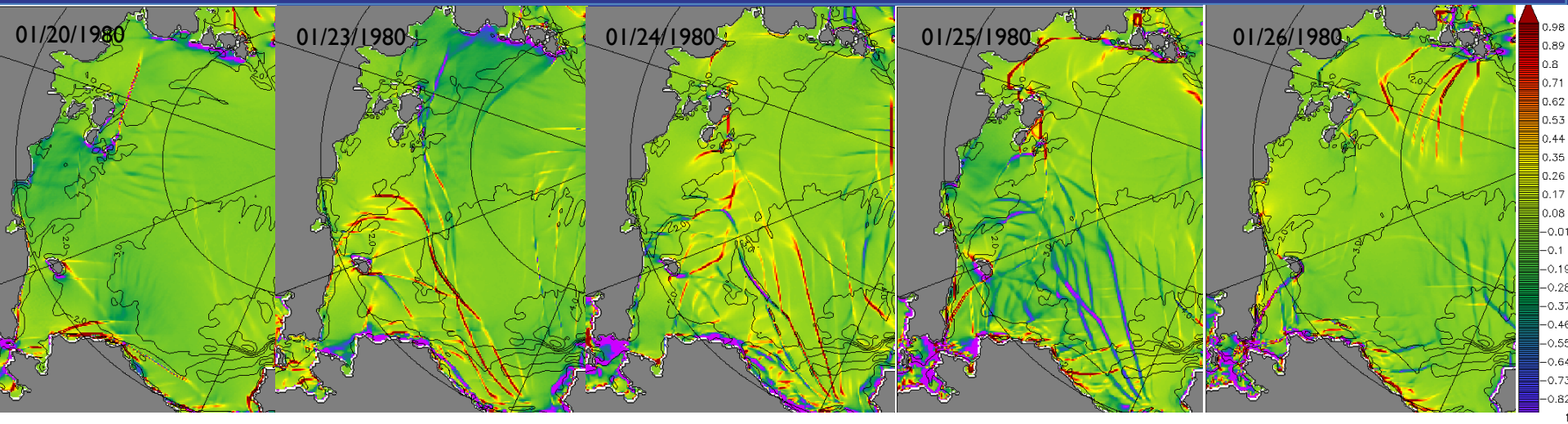




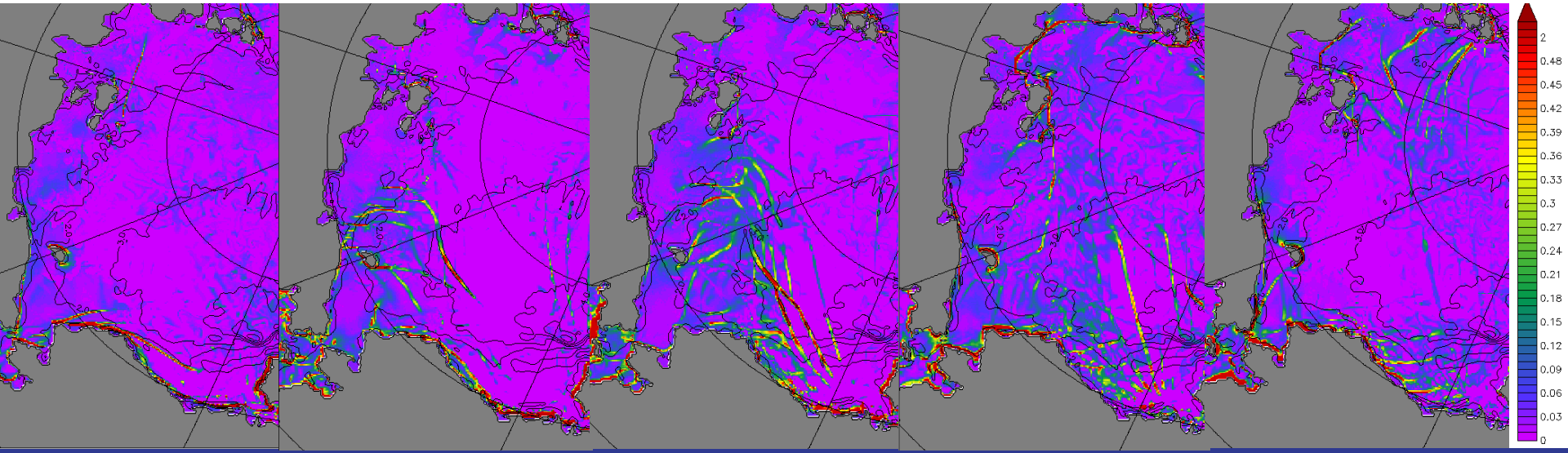
Average volume of level ice with: EVP: **6023 km³** EAP: **6535 km³** (+8%);
Average volume of ridged ice with: EVP: **7942 km³** EAP:**11201km³** (41%);
Mean sea ice volume with **EAP** is **~27%** higher compared to **EVP** **in fully coupled RASM**
and **~13%** higher compared to **EVP** **in forced ice-ocean RASM-G**

RASM Deformations: Impact of a Storm

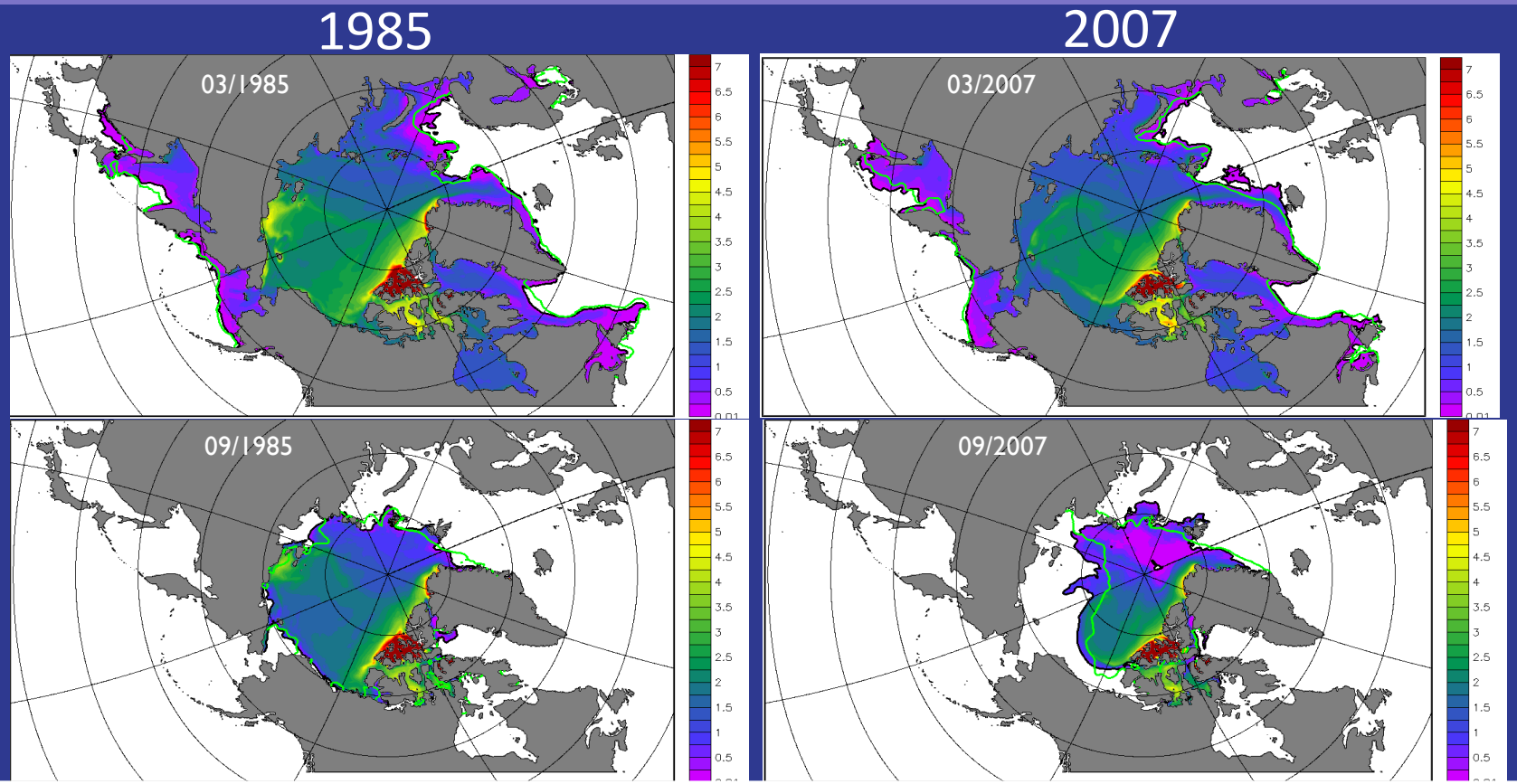
Daily divergence (top) & frazil ice growth (bottom) in fully coupled RASM with EAP

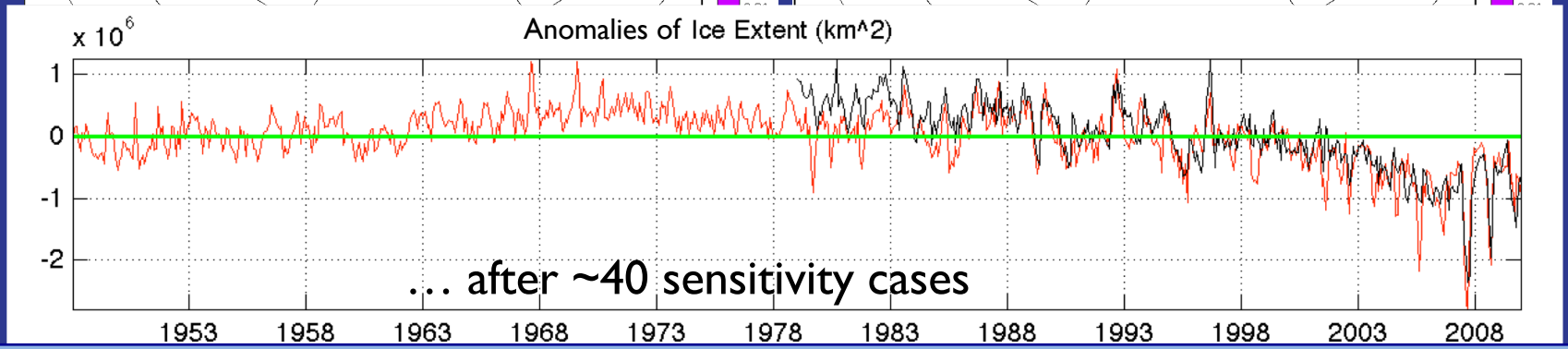


An example of storm produced deformations and ice growth & the need for high resolution

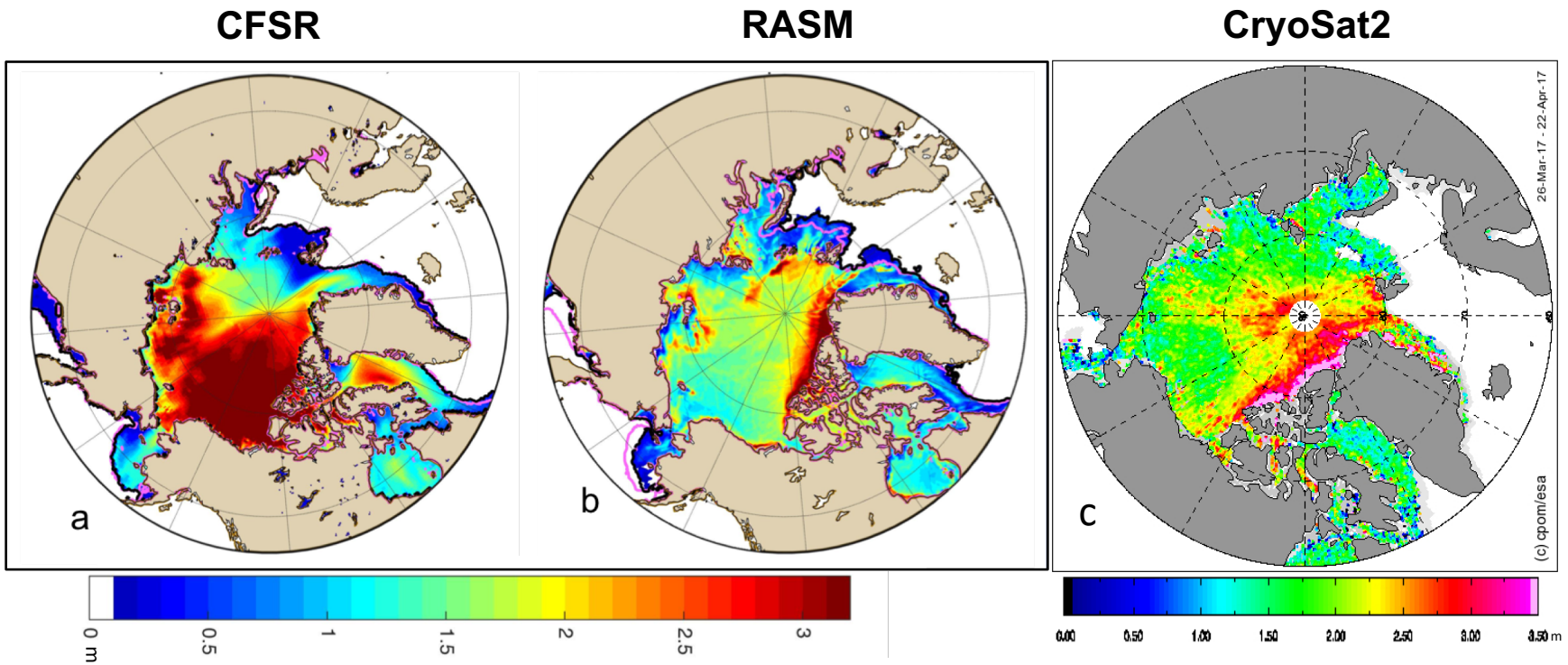


Optimizing Model Parameter Space - Sensitivity Studies





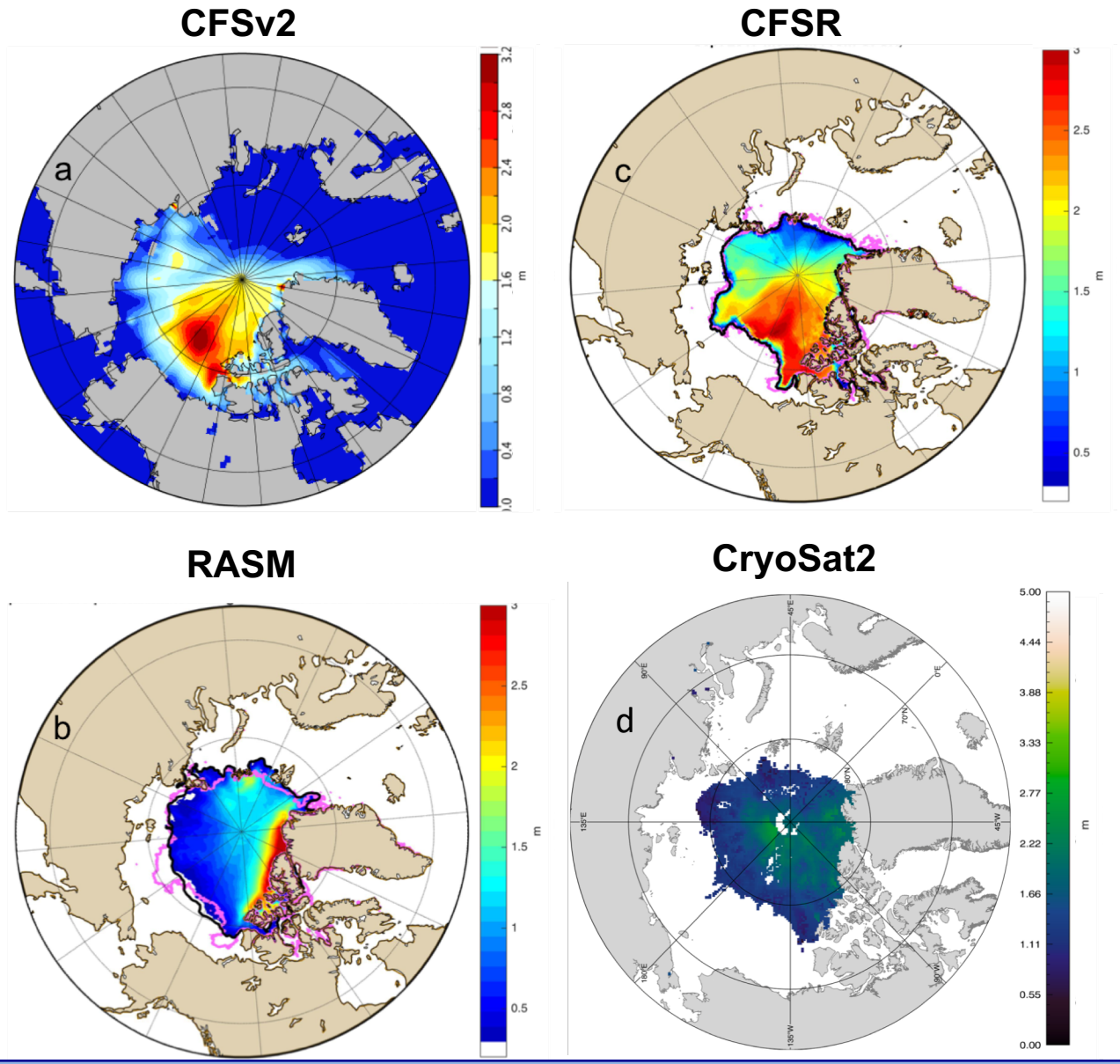
Dynamical Donwscaling of CFSR using RASM



Initial Value Problem

Initial conditions of the Arctic sea ice thickness distribution (m) on April 1, 2017 estimated from (a) CFSR with data assimilation of sea ice concentration, (b) RASM forced with CFSR forcing for 1979-2017, and (c) the 28-day CryoSat2 composite for 26 Mar - 22 Apr, 2017. The black / purple contours represent the respective model / SSMI 15% ice concentrations for the same day.

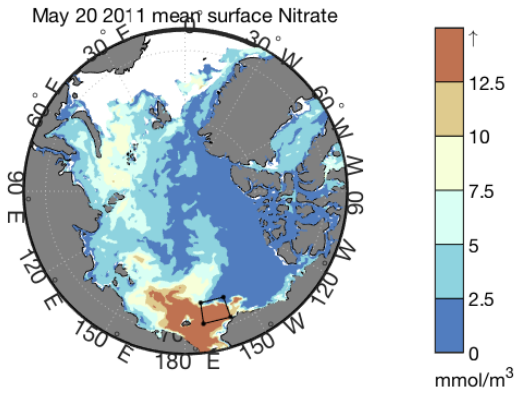
Dynamical Donwscaling of CFSv2 using RASM

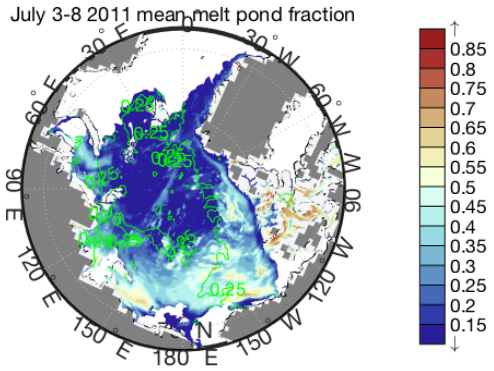


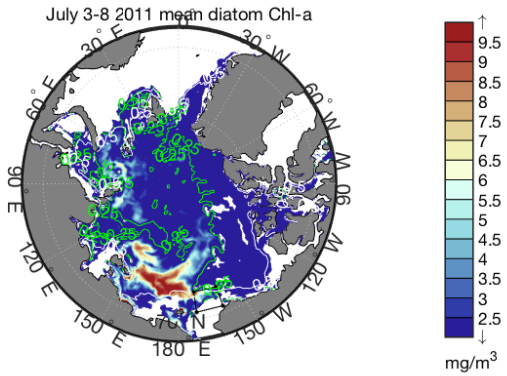
Boundary Value Problem

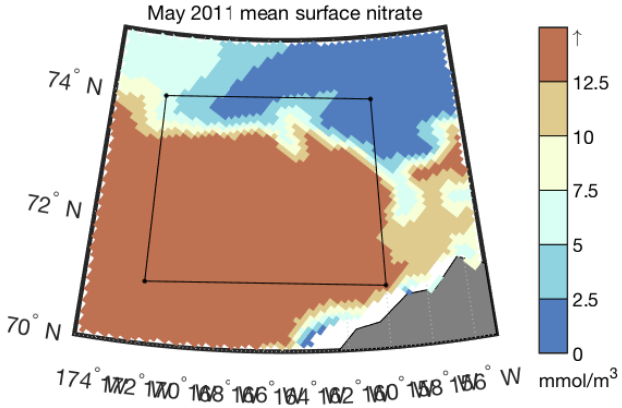
6-month forecasts of sea ice thickness distribution (m) from: (a) CFSv2 on 15 Sep., 2017 and (b) RASM Sep. monthly-mean of 2017, forced with the CFSv2 output; (c) CFSR reanalysis of sea ice thickness for Sep. monthly-mean of 2017, with data assimilation of sea ice concentration; (d) the 16-day (15 Sep - 1 Oct, 2017) CryoSat2 composite estimate of sea ice thickness. The black and purple contours in (b & c) represent the respective RASM & CFSR and observed 15% ice concentrations.

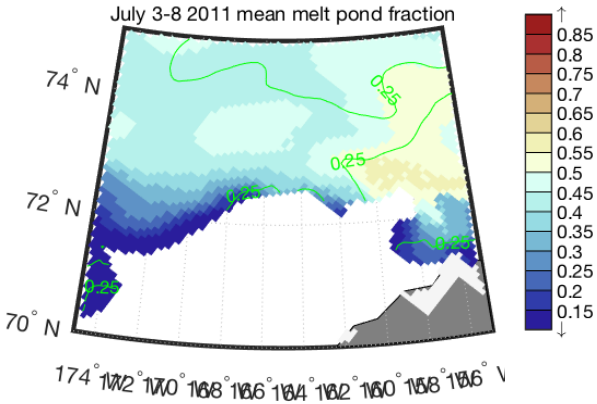
Regional Arctic System Model (RASM) - mBGC

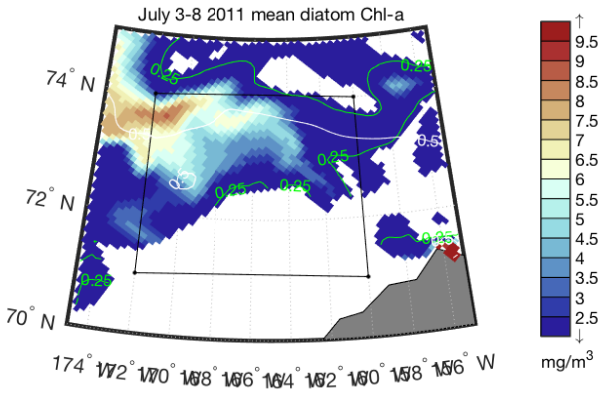












(left) Sea-surface nitrate concentrations two weeks before the June under-ice bloom in 2011; (middle) Melt pond fraction for July 3-8 2011; and (right) Mean surface diatom Chl-a for July 3-8 2011, for ice concentration > 15%.
Green contours delineate where Chl-a > 2.5 mg/m^3, indicating a bloom.
White contours delineate where ice concentration > 50%.

Frants et al. (in prep.)

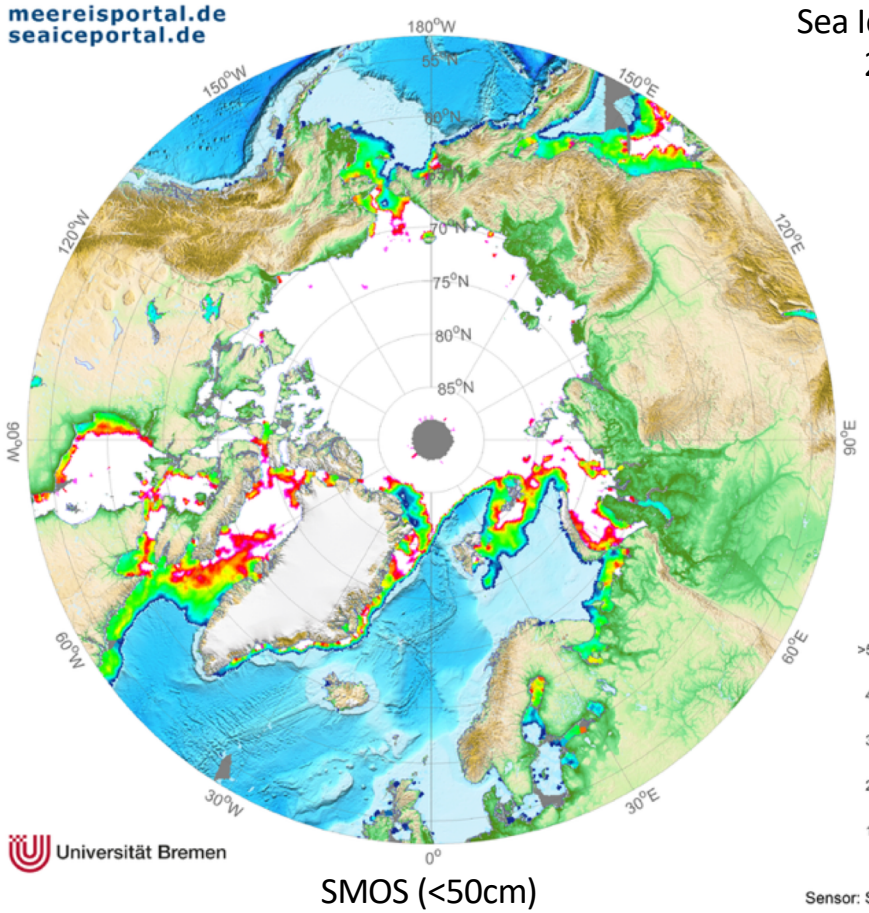
Summary

1. Process-resolving regional and global Earth system models have potential to reduce uncertainty and improve prediction at sub-seasonal to decadal time scales
2. Fully coupled climate models are necessary to truly understand the role of processes, feedbacks and coupling channels in the Arctic climate system
3. Scale-aware model physical parameter space requires careful optimization:
   - An ocean model at 2-km resolution should not use the same parameters (e.g. viscosity, diffusivity, convection) as one at 100-km
   - In such a context, optimization is not a bad thing but a requirement
4. A new sea ice model needed for resolution of O(1km) or less
5. A new level of observational detail / data is required to constrain process resolving regional and global Earth system models

Thank You!

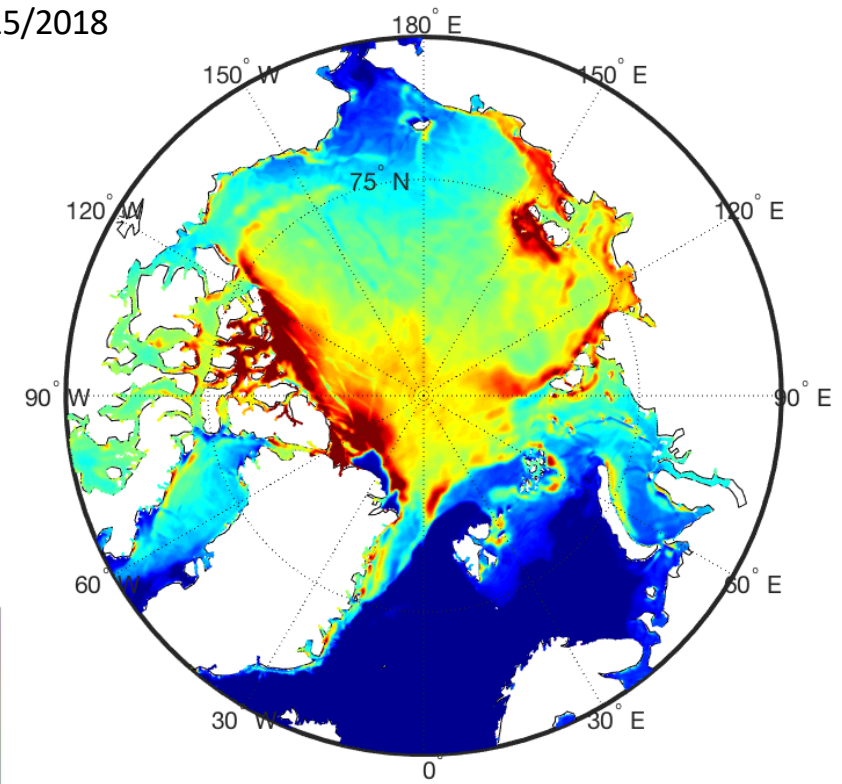
RASM Simulation of an Event in Space and Time

The polynya north of Greenland in late February 2018



SMOS (<50cm)

Sea Ice Thickness on
2/25/2018

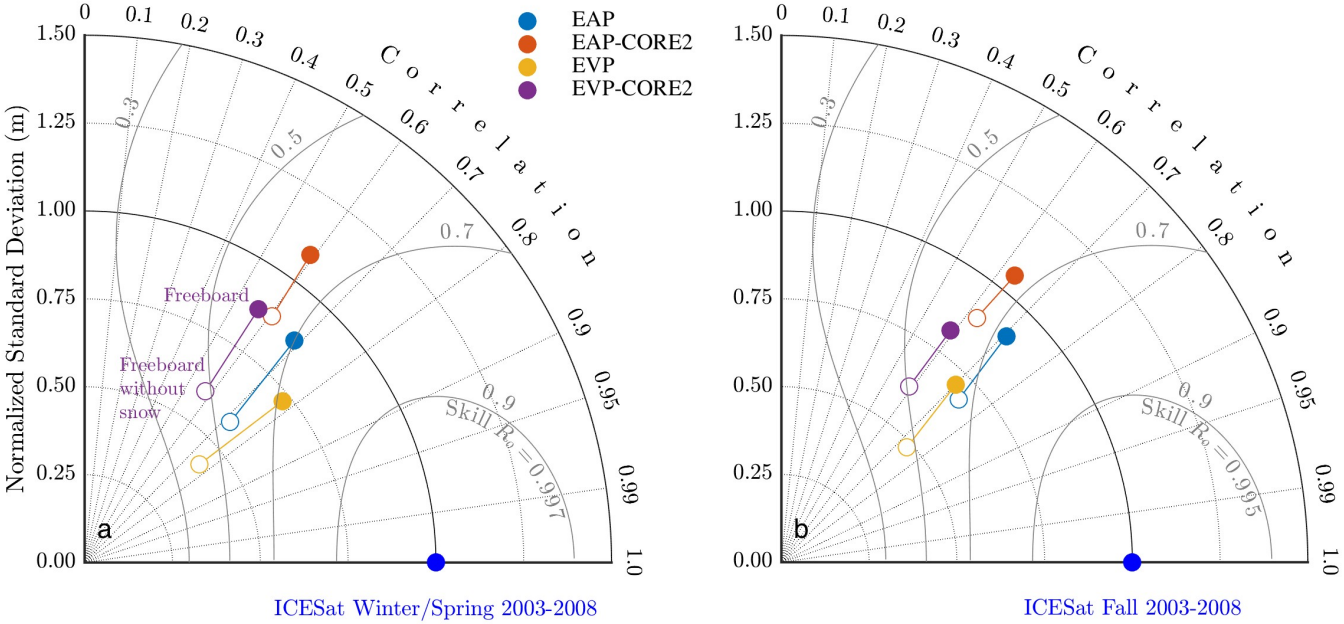


RASM

Lee et al. (in prep.)

New Analysis Techniques for CICE: Skill Metrics

RASM Version 1 Freeboard Performance for the Arctic Ocean



Further details of the skill score available in:
Roberts, A.F., E.C. Hunke, R. Allard, D.A. Bailey, A.P. Craig, J.-F. Lemieux, M. D. Turner (2018). Quality Control for Community Based Sea Ice Model Development, Phil. Trans. R. Soc. A. accepted, doi:10.1098/rsta.2017.0344.

Quantifying Model Skill – Taylor Skill Scores

Model	Institution	Atmosphere	Ocean	Sea Ice
CESM-LE	National Center for Atmospheric Research	CAM5 30 levels at ~1°	POP2 60 levels at ~1°	CICE4
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory	Included 48 levels at 200 km	MOM4.1 50 levels at 1°	SIS
HadGEM2-CC	Met Office Hadley Center	HadGAM2 60 levels at ~1.6°	Included 40 levels at 1.875°	Included
MPI-ESM-MR	Max Plank Institute for Meteorology	ECHAM6 95 levels at 1.8°	MPIOM 40 levels at 1.5°	Included
RASM	Naval Postgraduate School	WRF At 50 km	POP 45 levels at 1/12°	CICE5

DiMaggio et al. (in revision.)